Three-Dimensional Echocardiography by Semi-Automatic Border Detection in Assessment of Left Ventricular Volume and Ejection Fraction : Comparison With Magnetic Resonance Imaging

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Abstract

The feasibility of three-dimensional echocardiographic reconstruction by semi-automatic border detection to assess left ventricular volume and function was investigated in a clinically applicable setting in 23 patients with various cardiac diseases and 7 normal volunteers.

The commercial equipment permits digital acquisition of three apical orthogonal views, manual tracing of end-diastolic and end-systolic endocardium, semi-automatic border extractions of other frames, three-dimensional echocardiographic reconstruction and dynamic display within 20 min in a low resolution mode. Correlation of measurements with data obtained by magnetic resonance imaging (MRI) using the biplane modified Simpson method showed left ventricular end-diastolic volume ($y=0.894x-0.456$, $r=0.925$, $p<0.001$), end-systolic volume ($y=1.09x-8.98$, $r=0.959$, $p<0.001$), and ejection fraction ($y=0.956x+1.93$, $r=0.851$, $p<0.001$). In addition, a dynamic three-dimensional "movie-like" image displayed the shape, geometry, and regional wall motion abnormality, and change in global shape and size of the left ventricle.

Three-dimensional echocardiographic analysis by three apical orthogonal views and dynamic display of the left ventricle provides reliable data comparable to MRI measurements within a reasonable period of time, and is now clinically feasible.

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Key Words
Echocardiography (three-dimensional), Ventricular function, Ejection fraction, Magnetic resonance imaging

INTRODUCTION

Information on left ventricular volume is important for monitoring patients with valvular disease, cardiomyopathy and myocardial infarction[1]. Accurate and repeatable measures of chamber volume would be useful in evaluating the ventricular status during medical or surgical treatment. Although biplane cine left ventriculography has been the most frequently used clinical reference standard, angiographic methods assume that the left ventricle is ellipsoid in shape, involve radiation and require

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invasive cardiac catheterization[2]. Echocardiography, a truly noninvasive technique that uses no ionizing radiation, theoretically would be ideal for repeated studies. However, current echocardiographic devices provide only two-dimensional views of the heart. While various two-dimensional echocardiographic approaches for measuring left ventricular volume have been described, such methods make assumptions about cavity shape and about the geometric relationship between the different tomographic imaging planes[3-5]. In addition, to appreciate three-dimensional structural relations, an experienced observer must make a mental reconstruction of the two-dimensional views.

Recently, improved computer-based applications have been implemented to reconstruct three-dimensional images from the two-dimensional images. Magnetic resonance imaging (MRI), another noninvasive technique, provides high-quality images of the heart, although they are not real-time and the procedure is rather time-consuming. We previously validated MRI measurements obtained *in vivo* as a comparable method for determining the left ventricular volume, compared with the true Simpson method and biplane cine left ventriculography[6].

The present study evaluated the feasibility of three-dimensional echocardiographic reconstruction by the three standard transthoracic apical views and semi-automatic border detection in assessment of the left ventricular volume and function in the clinical setting, with MRI used as the standard of comparison.

METHODS

Patient selection

We initially enrolled 31 consecutive subjects who underwent MRI and three-dimensional echocardiographic studies at the Fujita Health University Hospital between June 1993 and March 1994. All subjects gave their informed consent for participation. One normal volunteer was excluded because of technically inadequate apical echocardiographic images. No subject was excluded because of technically difficult MRI studies. The remaining 30 subjects (23 patients with various cardiac diseases and 7 normal volunteers) were evaluated. There were 26 men and 4 women with a mean age of 58 years (ranged from 22 to 83 years). All subjects had normal sinus rhythm. Diagnosis included coronary heart disease ($n=12$), hypertrophic cardiomyopathy ($n=5$), valvular heart disease ($n=4$), and dilated cardiomyopathy ($n=2$). Eight of 12 patients with coronary heart disease had apical or posterior aneurysm.

Three-dimensional echocardiographic volume measurements

We used an ultrasound scanner (CFM-800, VINGMED Sound, Norway) combined with an integrated personal computer (Apple Macintosh II series, U.S.A.). Using a 2.5 MHz annular array transducer placed at the apex of the heart, we visualized apical four-chamber, two-chamber, and long-axis views, which were identified by anatomic landmarks. The four-chamber plane was assigned as 0°, and the other planes were assumed to be 62° and 101° counterclockwise, respectively.

For each imaging plane, sequential images from one cardiac cycle (electrocardiography : ECG gated from one R wave to next R wave) were sampled and transferred as digital scanline data to the computer. The captured cycle then was played back in a continuous loop to examine whether the endocardial definition would be sufficient or not. If sufficient endocardial definition could not be obtained or the patient moved during image acquisition, that data set was discarded and the procedure was repeated. The endocardial borders of all three imaging planes were manually traced in end-diastole (defined at the R-peak on ECG) and end-systole (defined at the frame of smallest left ventricular area). All other frames during the entire cardiac cycle were then automatically traced by a computer algorithm, which allowed the ventricular endocardium to be traced at the echogenic transition zone between manual end-diastolic and end-systolic tracings.

The traces on each freeze frame image were repeatedly evaluated against the moving endocardium by use of the cineloop replay function, and the investigator could manually adjust appropriate tracings if a computer algorithm traced inappropriate endocardial contours.

The surface of endocardium in three-dimensional space was generated using bi-cubic spline interpolation in order to obtain a surface with minimal variation in curvature[7]. While the resolution of the three-dimensional reconstruction could be set as low (16 slices), middle (32 slices) or high (64 slices), we used the low resolution to clarify the clinical applicability of this method for reducing time for volume computation by three-dimensional echocardiography. Tracings were positioned in three-dimensional space with respect to the relative angles between the image planes, and by alignment of the ventricular apex in origin and the left ventricular long axis.

The apex was determined by the computer as the point of the tracings most distant from the midpoint of the mitral plane. Since skewed or foreshortened image planes would underestimate volumes to cause errors in the reconstructed endocardial surface, contours were stretched in the direction of the major axis so that all major axes were equal to the longest axis obtained.

The cavity volumes of one cardiac cycle were calculated automatically by disk summation (Simpson's rule). The area of each cross-section disk was obtained from the mathematical description of the cubic spline curve, and disk volume is calculated as the product of disk area and height where the latter is given as the major long-axis length divided by the selected axial resolution.

About 15 min per subject was required for image acquisitions and both manual and semi-automatic endocardial border tracings. An additional 5 min was necessary for volume computation by three-dimensional echocardiography in the low resolution mode. Three-dimensional echocardiographic reconstructed end-diastolic and end-systolic volumes and ejection fraction measures were compared with data obtained by MRI using the biplane modified Simpson method. MRI was done within 2 weeks of three-dimensional echocadiographic evaluations in each subject.

Biplane ventricular volume measurements by MRI

Biplane ventricular volume measurements by MRI used 0.5 tesla MRI system (MRT-50A, Toshiba, Japan). To detect the true left ventricular long-axis plane, the coronal slice of body was obtained at first, then a four-chamber slice (single oblique slice) was set against the previous coronal slice, and then a two-chamber slice (double oblique) against the previous four-chamber slice. We repeated the same processing several times, and finally the left ventricular vertical and horizontal long-axis planes passing through the apex and the center of the mitral valve were determined.

This method was named the chain (double) oblique technique. Thereafter, imaging was performed by an ECG gated gradient field echo that rephrased the cine mode sequence using a flip angle of 30°, an echo time of 22 msec, and a repetition time of 50 msec. ECG gating was started 2 msec after the R wave, and 80% to 85% of an average RR interval was divided into 13 to 16 frames. The first frame was specified as the end-diastolic image, and the frame with the smallest image was selected for the end-systolic image.

The left ventricular cavity was manually outlined with a trackball on the end-diastolic and end-systolic images. Left ventricular volume was calculated using the biplane modified Simpson method, in which the left ventricular short-axis plane is assumed to be elliptical. The average imaging time per study was 30 min; the total study time was 1 hour[6].

Statistical analysis

Three different analyses were performed to evaluate the validity of three-dimensional echocardiographic and MRI data: linear regression, to identify a predictable relation between three-dimensional echocardiographic and MRI data; Bland-Altman analysis, to quantify bias between variable values obtained with the two techniques and to determine the predictable value (population error) of three-dimensional echocardiographic measurements in individual subjects[8]; and the Student's *t*-test for matched pairs, to ascertain the statistical significance of bias between values determined by two methods.

RESULTS

Table 1 shows the mean value ±SD of the two methods. The results of linear regression of three-dimensional echocardiographic volumes on MRI volumes are shown in **Fig. 1**. Results of Bland-Altman analysis are shown in **Fig. 2**. Using MRI, left ventricular volumes ranged between 38 and 270 m*l* at end-diastole and between 4 and 175 m*l* at end-systole. Data obtained by three-dimensional echocardiography ranged between 38 and 248 m*l* at end-diastole and between 4 and 200 m*l* at end-systole. The correlations (*r*) between MRI and three-dimensional echocardiographic values for end-diastolic and end-systolic volume were 0.925 and 0.959, respectively (**Figs. 1–left, middle**).

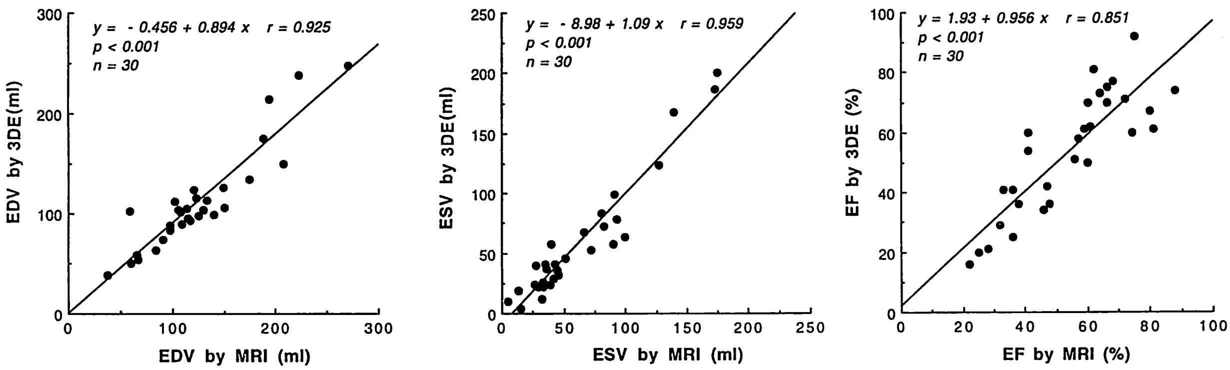


Fig. 1 Correlations between left ventricular end-diastolic (*left*) and end-systolic volumes (*middle*) and ejection fractions (*right*) measured by three-dimensional echocardiography (3DE) and by magnetic resonance imaging (MRI)

The values of two methods are plotted against each other. The line of identity has been superimposed.
EDV = left ventricular end-diastolic volume; ESV = left ventricular end-systolic volume; EF = ejection fraction.

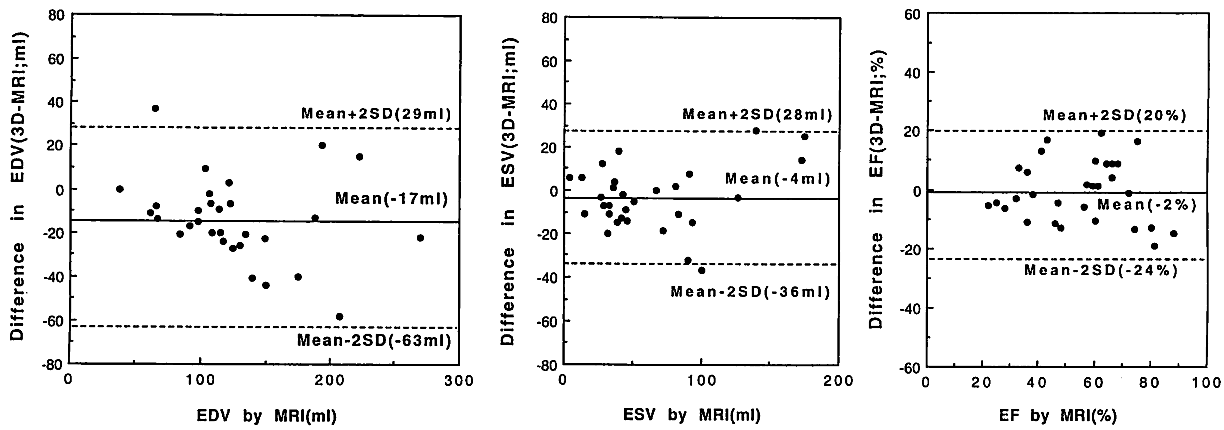


Fig. 2 Differences between three-dimensional echocardiographic and MRI values (vertical axis) plotted against the MRI values (horizontal axis), with 95% confidence limits in left ventricular end-diastolic and end-systolic volumes and ejection fractions

Dotted lines : mean difference ±2SD.
Abbreviations as in Fig. 1.

Table 1 Cardiac variables measured by three-dimensional echocardiography (3DE) and MRI

	3DE	MRI	*p* value
EDV (m*l*)	112±51	126±52	0.001
ESV (m*l*)	59±51	63±45	NS
EF (%)	54±20	54±18	NS
Heart rate (beat/min)	72±4	74±6	NS

Values are presented as mean ±SD.
Abbreviations as in Fig. 1.

Three-dimensional echocardiographically derived end-diastolic volumes had a tendency to have smaller values than the corresponding MRI ones in most of the subjects. The difference was significant, but the negative bias was small (−17 m*l*) and the 95 % confidence intervals for the difference were relatively narrow (−63 to +29 m*l*, **Fig. 2–left**). Conversely, three-dimensional echocardiographically derived end-systolic volumes were similar to the corresponding MRI values in most of the subjects. The difference was not significant, the negative bias was small (−4 m*l*) and the 95% confidence intervals for the difference were narrow (−36 to +28 m*l*, **Fig. 2–middle**). The ejection fraction ranged from 88% to 22% with MRI and from 92% to 16% with three-dimensional echocardiography. A significant correlation was observed between the left ventricular ejection fraction obtained by the two methods, with a regression equation close to the identity line ($y=0.956x+1.93$, $r=0.851$, $p<0.001$, **Fig. 1–right**). Three-dimensional echocardiographically derived ejection fractions were similar to the corresponding MRI values in most of the

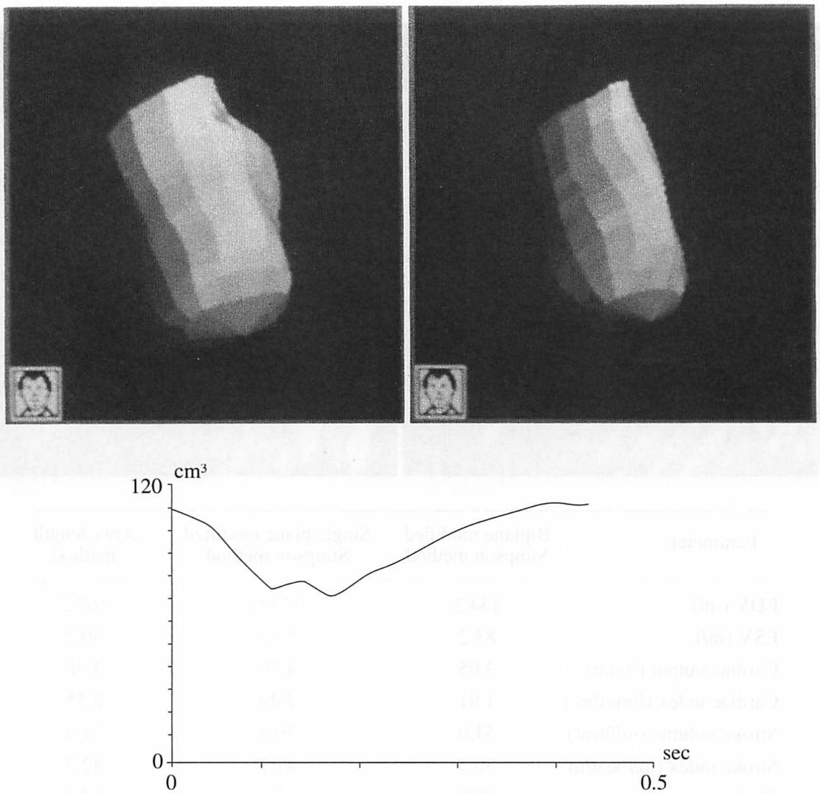


Fig. 3 Representative three-dimensional echocardiographic reconstructions of anterior left ventricular end-diastolic (*upper-left*) and end-systolic images (*upper-right*) of old myocardial infarction with apical aneurysm. The left ventricular volume curve and ejection fraction calculation are also shown (*lower*)
EDV : 113 cm^3, ESV : 72 cm^3, EF : 0.37.
Abbreviations as in Fig. 1.

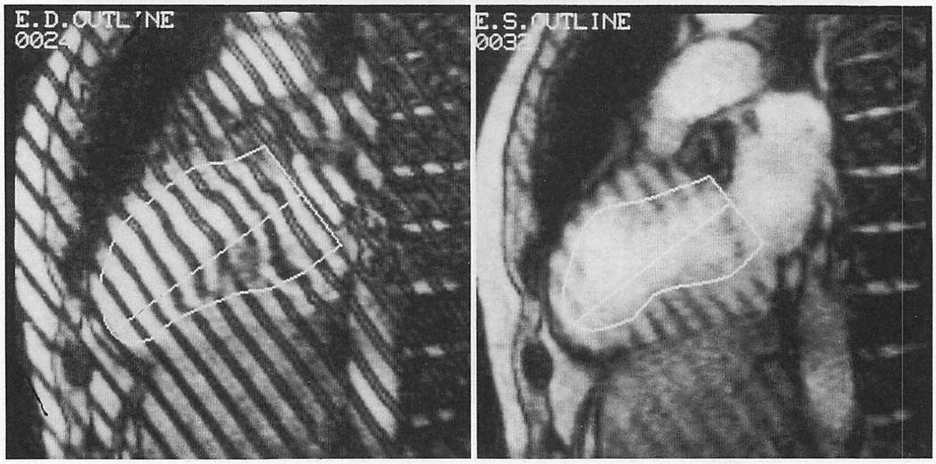
subjects. The difference was not significant, the negative bias was small (-2%) and the 95% confidence intervals for the difference were narrow (-24% to $+20\%$, **Fig. 2–right**). In addition, loops of the four-dimensional echocardiographic images dynamically displayed the left ventricular shape, geometry, regional wall motion abnormality, and change in global shape and size. This dynamic, four-dimensional "movie-like" image was also useful for identifying regional asynergy. The heart rate of the subjects during the echocardiographic examination was similar to that during the cine MRI examination (72 ± 4 vs 74 ± 6 beat/min, NS).

A representative set of three-dimensional echocardiographic images obtained at end-diastole and end-systole in a patient with an old myocardial infarction and an apical aneurysm is shown in **Fig. 3**. MRI data on that patient appear in **Fig. 4**. The end-diastolic and end-systolic volumes were slightly smaller in the three-dimensional measurements than in the MRI ones. Ejection fractions were quite similar to both measurements.

DISCUSSION

A three-dimensional reconstruction of the left ventricle would ideally provide reproducible data on chamber volume, shape and regional wall motion. It would be useful for clinical decision-making, offering new and unique information with accuracy similar to MRI. While three-dimensional imaging of the heart by ultrasound has been attempted for many years, several methods have been applied[7,9–13].

The major limitation of previous approaches is the time-consuming process of coordinating the cross-sections of the heart with their spatial locations, ambiguous displays and varying quality of the reconstructed image. Several methods have been proposed : Rotation of the imaging plane from the apical position during transthoracic imaging, tilting of the short-axis image plane from the parasternal position, and more recently, parallel short-axis images of the left ventricle obtained by transesophageal echocardiography.



Parameter	Biplane modified Simpson method	Single plane modified Simpson method	Area-length method
EDV (m*l*)	134.2	153.6	162.2
ESV (m*l*)	83.2	83.3	90.2
Cardiac output (*l*/min)	3.05	4.20	4.30
Cardiac index (*l*/min/m^2)	1.81	2.49	2.55
Stroke volume (m*l*/beat)	51.0	70.3	71.9
Stroke index (m*l*/beat/m^2)	30.3	41.7	42.7
EF (%)	38.0	45.8	44.4
Height (cm)	162.3		
Weight (kg)	62.7		
Body surface area (m^2)	1.68		
Heart rate (beat/min)	59.8		
Blood pressure (mmHg)	130/78		

Fig. 4 MRI left ventricular end-diastolic and end-systolic images of the patient appear in Fig. 3 and his clinical characteristics
Upper-left : End-diastolic right anterior oblique view. Left ventricular length diastole is 9.2 cm.
Upper-right : End-systolic right anterior oblique view. Left ventricular length systole is 7.9 cm.
Lower : Patient characteristics.
Abbreviations as in Fig. 1.

We used an algorithm to obtain a three-dimensional reconstruction of the left ventricle from three apical orthogonal views. This approach can be easily used in the clinical setting with specific anatomic landmarks and does not require any spatial registration. These three or four apical images produced volumes of symmetric and deformed *in vitro* objects accurately over a wide range of size and shape, and produced repeatable left ventricular volumes in clinical settings[7].

A reconstruction of the three-dimensional image using more than three apical echocardiographic views would seem to improve the performance of the algorithm. Recently, a minimum of eight to 12 intersecting or nonparallel images have been reported to be necessary for quantifying left ventricular volume and systolic function[14]. However, this would require an additional method of spatial registration, and would therefore be less practical in the routine clinical setting. In addition, echocardiographic images are influenced by variations in acoustic conditions induced by chest deformities or an abnormal relationship between the heart and lung. Therefore, complete acquisition of many images would not always be possible in the clinical setting, and could also potentially introduce errors when reconstructing the image.

Three-dimensional echocardiography reconstruction might be possible in this patient subset using the multiplane transesophageal echocardiographic approach[15]. This approach would seem most ideal in theory. However, the transesophageal echocardiographic approach is not comfortable for patients and not justified in every patient, especially for use only in estimating volume. In addition, positional instability of the transesophageal echocardiographic probe has been reported with implications for three-dimensional reconstruction and needs a specific sensor in the tip to identify the probe three-dimensional position and orientation in space[16].

The close correlation between our three apical orthogonal three-dimensional echocardiographic measurements of ventricular volume and ejection fraction with those obtained by MRI reflects the relative accuracy of the measurement obtained with this newer approach. Underestimation of the volume by three-dimensional echocardiography may be due to exclusion of the true apex of the left ventricle, especially at end-diastole, when the transthoracic echocardiographic approach is used[4].

The intravascular procedure used in cine-angiography and cine computed tomography is more stressful than cine MRI and might therefore tend to increase heart rate and could thus increase the inotropic state. These measurements would introduce some error in volume estimates[17].

We used MRI in this study as the standard for measuring ventricular volumes, since it is truly noninvasive, and is therefore useful in studying normal volunteers[18]. However, errors in MRI measurements still arise from definition of endocardial contours and from geometric assumptions inherent in the biplane modified Simpson method. Biplane methods were less accurate than multisection MRI in direct comparison, but a difference was attributed in part to off-axis imaging[19]. In a previous MRI study[6], we found that on-axis images showed a good correlation with multisection MR images. Another problem with MRI is its time-averaging image, in that end-diastolic and end-systolic volumes can vary from heartbeat to heartbeat. In many instances, it is difficult to determine "which standard has the gold"[20]. Considering the potential for error in both methodologies, the present results support the accuracy and clinical applicability of three-dimensional echocardiographic methods for measuring ventricular volumes[21,22].

Another usefulness of this study is dynamic three-dimensional echocardiographic analysis of the left ventricle using semi-automatic border detection. While automated border detection and volume calculations have been already reported, inherent problems with the systems were also pointed out[23,24]. These automatically calculated volumes were only obtained from one slice of a two-dimensional image and could introduce some errors, especially for patients with regional asynergy. In our system, manually traced endocardial contours of end-diastolic and end-systolic frames could reduce the errors to a minimum, especially for patients with excessive mitral annulus movement. In addition, loops of the three-dimensional echocardiographic "movie-like" images dynamically displayed the left ventricle and facilitated identification of left ventricular shape, geometry, and regional asynergy.

CONCLUSION

Three-dimensional echocardiographic analysis and dynamic display of the left ventricle obtained from three apical orthogonal views was clinically feasible and provided reliable data comparable to that obtained by MRI measurements within a reasonable time.

要　約

左室容積および駆出率計測における半自動境界検出三次元心エコー図法：磁気共鳴映像法との対比

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本研究の目的は半自動的辺縁検出法を用いた三次元心エコー図法により，左室容積と機能評価の臨床的実用性を検討することである．使用装置は CFM-800 (VINGMED Sound, Norway) で，対象は 23 例の心疾患患者と 7 例の健常ボランティアであった．

この装置は心尖部からの四腔，二腔，長軸の 3 断面をデジタルデータとして記録し，拡張お

よび収縮末期画像の心内膜面をマニュアルトレースした後，残りの画像を半自動的にトレースし，低解像度モードでは20分以内に三次元心エコー像を構築して，動画像として表示することが可能である．計測データは2断面修正Simpson法を用いた磁気共鳴映像法(MRI)のデータと比較した．

MRIとの相関は，左室拡張末期容積では$y=0.894x-0.456$, $r=0.925$, $p<0.001$，収縮末期容積では$y=1.09x-8.98$, $r=0.959$, $p<0.001$であり，駆出率では$y=0.956x+1.93$, $r=0.851$, $p<0.001$であった．更に，三次元心エコー図法による動画表示は左室の幾何学的形態と局所壁運動異常を時間的変化として表示可能であった．

心尖部からの3断面を用いた三次元心エコー図法による左室解析と動画表示は，MRIに匹敵する信頼性をもって納得しうる時間内に計測可能であり，臨床的に適応可能な方法と考えられた．

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